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IIIII Development of Boiling and Two-phase Flow Experiments on Board ISS IIIII
(Review)

Development of Boiling and Two-phase Flow Experiments on Board ISS (Research Objectives and Concept of Experimental Setup)

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Abstract

Boiling and two-phase flow attract much attention for the improvement of cooling and heat dissipation processes on the ground and in space. However, there is very limited number of experimental data and no systematic or no coherent data needed for the design of space thermal management systems. In addition to establish the framework of database for boiling and two-phase flow in microgravity, the clarification of dominant force regime map is of top importance. Once the operating conditions free of gravity effect are clarified, reliable space systems can be developed by the iteration of ground tests. Furthermore, two-phase mixtures involving vapor phase can be transported independent of its orientation in the terrestrial cooling systems. Flow boiling experiments is planned onboard ISS by JAXA in 2016. In the present paper, individual subjects in the regimes of nucleate boiling and two-phase forced convection and the subjects in liquid-vapor interfacial behaviors are discussed by the citation of the results from the experiments of short microgravity duration, and the design concept of experimental setup under the restrictions inherent in the space experiment is described including the structures of test sections already integrated in PFM.

Keyword(s): Boiling, Two-phase flow, Microgravity, Heat transfer, Critical heat flux, International Space Station
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1. Introduction

Boiling and two-phase flow are phenomena which are expected to be utilized for the improvement of cooling systems on the ground because the inherent latent heat transportation realizes the removal and transportation of a large amount of heat and the cooling at high heat flux density from the semiconductors. These advantages attract much attention for the cooling of automobile inverters and of data servers which are requested to reduce the size and increase the capacity in order to promote the energy conservation and to develop innovative communication systems, respectively. The situation holds true also in space, where the energy consumption tends to increase for the enlarged space missions accompanied by the increase in the amount of heat dissipated and in the distance for the transportation of waste heat to the radiators.

On the ground, in almost all of existing cooling and thermal management systems except the systems of refrigeration cycle using compressors, single-phase liquid is used as a coolant. The application of two-phase system is very limited on the ground and in space except the employment of heat pipes. The advantages for the application of boiling and two-phase system are summarized as follows. i) The cooling at high heat flux density is useful for the semiconductors with increased heat generation density and for the unexpected increase in the amount of dissipated thermal energy even in the liquid cooling systems. The increase of heat flux density from the semiconductors in the near future is unavoidable not only on the ground but also in space. ii) The reduction of mass flow rate is possible due to the latent heat transportation during the evaporation, which results in the saving of pump power, and in turn the reduction of liquid inventory and of launch mass. iii) Once the fluid temperature becomes saturated, the temperature is kept at the saturation temperature even by the additional heat input. The surface temperature never gradually increases toward the downstream as is observed in the cooling systems using

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single-phase liquid. Such a situation is useful for the cooling of semiconductors under the restriction of low operating temperature.

On the other hand, the boiling and two-phase systems, however, have disadvantages at the same time. The operating conditions should be selected not to induce the burnout or dry out so that the rapid increase of surface temperature does not damage the electronic devices.

The most serious problem to develop space two-phase thermal management systems is the poor knowledge about flow boiling behaviors under microgravity conditions. For example, there is almost no reliable date for CHF conditions in flow boiling. JAXA is planning to perform a series of flow boiling experiments onboard ISS (International Space Station) in 2016, and the flight model of experimental setup is under final testing. In the present paper, the objectives of individual subjects to be investigated utilizing long-term microgravity duration are described and the outline of experimental setup with devised structures to satisfy the scientific requirements is introduced. The existing experimental studies on boiling in microgravity are reviewed by Merte [1)], Straub [2)], Di Marco et al. [3)] and Zhao [4)], Di Marco et al. [5)] and Ohta et al. [6)]. The last article gives the latest information about flow boiling in microgravity.

Nomenclature

Bo	Bond number
d	tube diameter (m)
Fr	Froude number
G	mass velocity (kg/m^{2}s)
g	gravitational acceleration (m/s^2)
P	pressure (Pa)
q	heat flux (W/m^2)
q_{CHF}	critical heat flux (W/m^2)
t	time (sec)
T	temperature (°C)
u	flow velocity (m/s)
x	vapor quality
We	Weber number

Greek letters

α	heat transfer coefficient (W/m^{2}K)
δ	thickness of macrolayer or microlayer (m)
ΔT	temperature difference (K)
σ	surface tension (N/m)
ρ	density (kg/m^3)

Subsripts

i	inner
l	liquid
m	mixture
out	outlet
sub	subcooling
v	vapor
w	wall

2. Knowledge to be clarified in TPF experiments

2.1 Two important subjects

The first subject is to clarify the effect of gravity on the heat transfer characteristics in flow boiling. The subject includes the gravity effects on both of heat transfer coefficient and critical heat flux (CHF). The second one is to clarify the conditions where gravity effect disappears. These subjects have an importance in the design of cooling systems applied to the space. If the system operates under the conditions where the gravity effect exists, the verification of the system performance under microgravity conditions cannot be omitted because of its reliability in orbit. And, it requires additional period and labor to obtain the data in microgravity. Once the system is designed under the conditions free of gravity effect, the iteration of ground tests can predicts the operation in orbit with high accuracy and reliability. To make a dominant force map will meet this requirement.

Two subjects are to be clarified systematically in a wide range of experimental parameters except those of CHF conditions where the limitation of power supply restricts the number of parameter combinations. Under almost constant pressure of 0.1 MPa, mass velocity, vapor quality at the inlet of the test sections and heat flux are three major parameters combined. The details of individual subject are explained in the following sections.

2.2 Gravity effects on heat transfer characteristics

The heat transfer regime for flow boiling is divided into two major regimes. One is the regime dominated by nucleate boiling and the other is by two-phase forced convection.

The former heat transfer is similar to nucleate boiling in a pool. However, the bubbles are exposed to the fluid flow, and are deformed by the shear stress exerted by the flow and/or are coalesced when the fluid contains the bubbles generated in the upstream. The gravity effect on an enlarged single bubble is depicted in Mode 1, **Fig. 1** [7)]. The key phenomena which affect the heat transfer is the behavior of thin liquid film often referred to as a microlayer and the dry patch extended in the center of the microlayer as the bubble growth. The structure was confirmed by the pictures in **Fig. 2** obtained from the TR-1A experiments by NASDA using a transparent heating surface in a pool [8)]. The existence of bulk flow elongates the bubble attached area and change the distribution of areas occupied by the microlayer and the dry patch. In addition, the bubble detachment from the tube wall is promoted by the flow of liquid in μG and upward flow in 1G. The bubble growth is ended by the bubble detachment, which influence the history of liquid-vapor behaviors at the bottom of the bubbles in a bubble cycle. In general, two conflicting trends exist, i.e. heat transfer enhancement due to the evaporation of thin liquid film and the

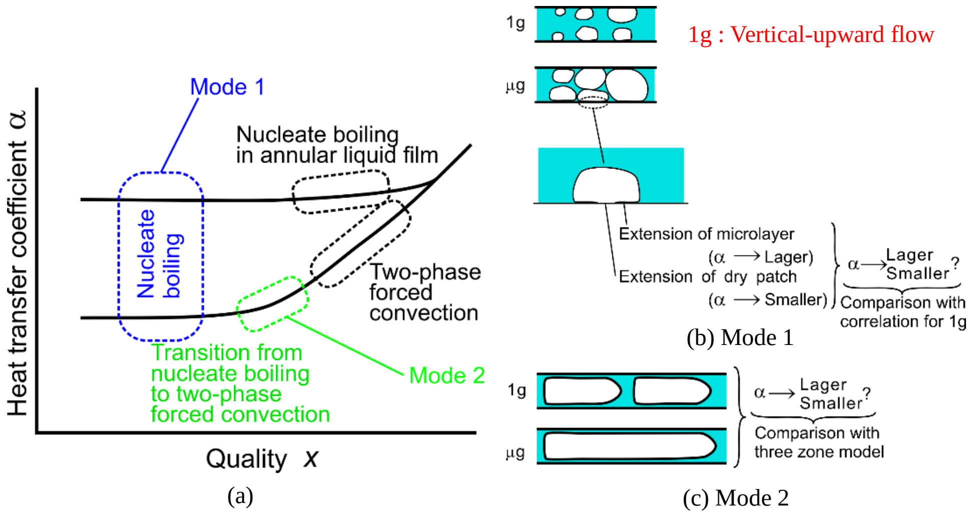


Fig. 1 Gravity effects on heat transfer and their mechanisms in bubble and slug flow regimes for vertical-upward flow [7].

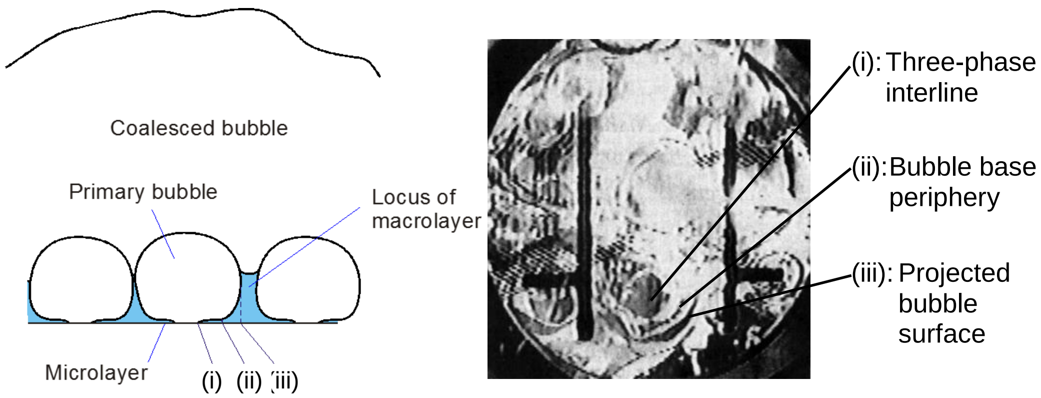


Fig. 2 A structure of bubble base composed of microlayer and dry patch observed for ethanol at 0.01 MPa [8].

deterioration due to the extension of dry patch during a bubble growth period. The heat transfer coefficients in nucleate boiling, however, is quite insensitive to the change of gravity as shown in **Fig. 3**, which was obtained from a series of experiments by aircraft [9]. The trend is quite contradictory to the gravity effects described above, and is a subject to be clarified in ISS experiment.

The flow pattern is changed from bubble flow to the slug flow when the vapor quality, defined by the mass flow rate of vapor to the total, is increased. The emergence of elongated bubbles referred to as Taylor bubbles is observed. There is a liquid film around a Taylor bubble, and three different modes of heat transfer exists. (i) Heat transfer to the liquid slug flowing between the Taylor bubbles, where heat transfer is dominated by the heat conduction to liquid of infinite body in the case of a short passage period of the liquid slug. (ii) Heat conduction across the film around a Taylor bubble. Even though the initial film thickness is far larger than the microlayer in bubbly flow regime, its contribution to the heat transfer in slug flow regime is large. (iii) Heat transfer to the vapor after the complete evaporation of the liquid film. These three mechanism is compiled by the three-zone model [10]. In most cases, the mode (iii) is not observed at least in 1G. However, the emergence of dries area is triggered also by the nucleate boiling in the liquid film, where the generation of bubble at high heat flux extends the microlayer and the dry patch simultaneously, and the extension of dry patches results in the local dryout around the Taylor bubble. In μG. The length of a Taylor bubble becomes far larger, which implies the increased probability of the mode (iii). The initial thickness of liquid film becomes a key parameter to apply the modes (ii) and (iii). The accurate evaluation of initial film thickness is needed under various conditions of experimental parameters. The situation is shown in Mode 2, **Fig. 1**.

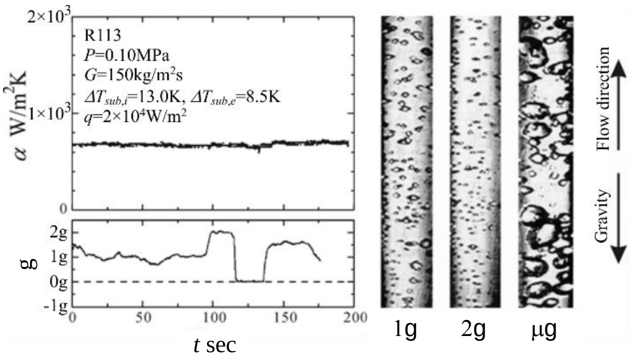


Fig. 3 Gravity effect on bubble behavior and heat transfer in bubble flow regime under subcooled condition of liquid flow [9].

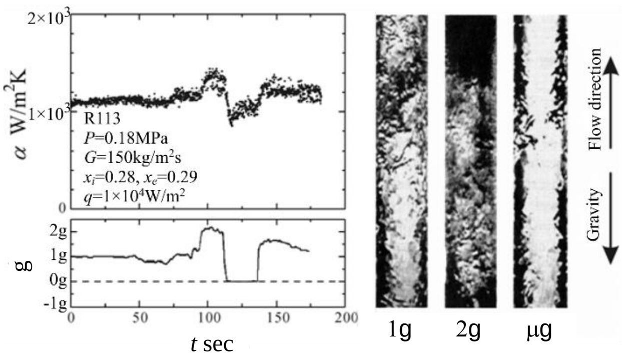
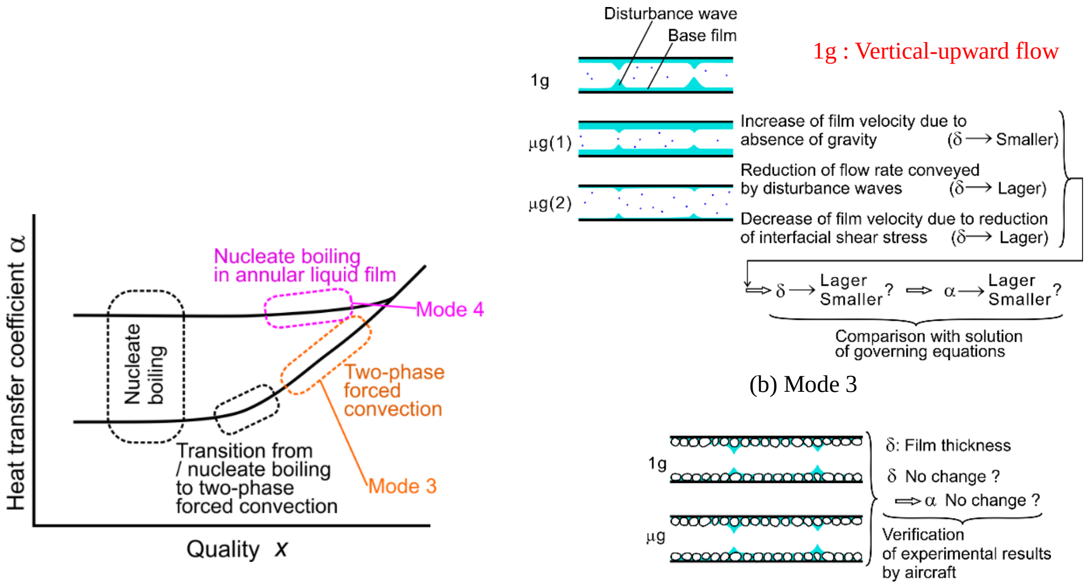


Fig. 4 Gravity effect on annular film behavior and heat transfer in annual flow regime at moderate vapor quality [9].



(a)

(b) Mode 3

(c) Mode 4

Fig. 5 Gravity effects on heat transfer and their mechanisms in annular flow regime for vertical-upward flow [7].

As further increase of vapor quality, the flow pattern is shifted to annular flow. The structure of annular flow is vapor core flow surrounded by annular liquid film attached to the inner wall of the tube. The annular flow is observed in a wide range of vapor quality and has an importance of practical application on the ground and in space. Except at high heat flux, nucleate boiling is suppressed and the heat transfer is dominated by two-phase forced convection to the liquid film. In general, the liquid-vapor interface is not smooth and the liquid film thickness changes with time accompanied by the periodical passage of disturbance waves. The heat transfer coefficient is influenced directly by the liquid film thickness and the turbulence in the film flow.

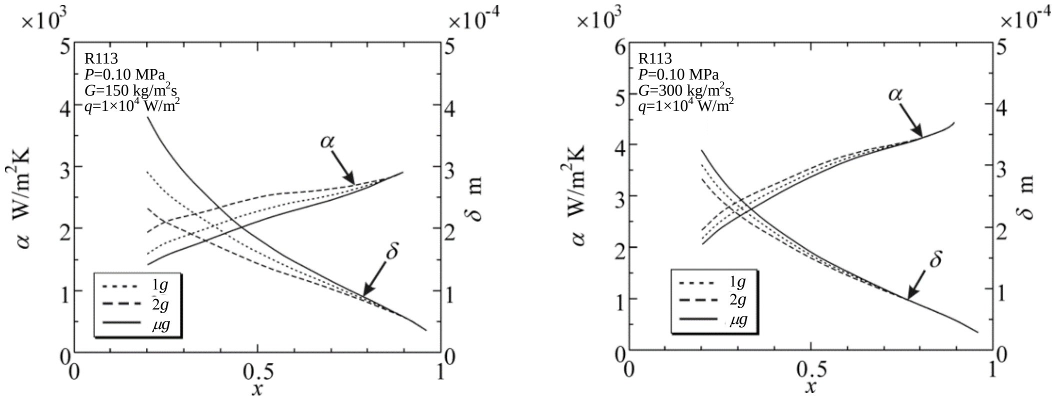
According to the experiment by aircraft [9], the heat transfer due to the two-phase forced convection is enhanced in hyper gravity (2G), while it deteriorates in μG as shown in **Fig. 4** for R113 at x=0.28 and G=150 kg/m^{2}s under P=0.18 MPa. The reason of variation in the observed heat transfer is often discussed by only the change of liquid film thickness. However it was revealed that, the level of turbulence also affects the heat transfer via the change of shear stress level in the liquid flow[11]. In microgravity, the reduction of gravity increases the velocity of the liquid film in the upward flow in 1G, which in turn decrease the film thickness provided that the same liquid flow rate is concerned. This trend enhance the heat transfer in microgravity in contrast to the experimental result. The second effect is the change of flow rate in the film flow. In microgravity, the both of the height and the length of a disturbance wave is smaller despite of no large change of passing frequency, which increases the film flow rate and its thickness if the change of entrained liquid droplets in the vapor core flow is ignored. Furthermore, the disturbance on the liquid-vapor interface is reduced in μG, which also decreases the level of turbulence in

		Low x	Moderate x	High x
High G		NB	TFC	TFC
Low G	High q	NB	NBA	NBA
	Low q	NB	TFC	TFC
Extremely low G		NB	NBA	NBA

G : Mass velocity
X : Vapor quality
Q : Heat flux
NB : Nucleate Boiling
TFC : Two-phase Forced Convection
NBA : Nucleate Boiling in Annular film

(blue box) : Gravity effect on liquid-vapor behavior
(yellow box) : Possible gravity effect on liquid-vapor behavior
(solid orange frame) : Gravity effect on heat transfer
(dashed orange frame) : Possible gravity effect on heat transfer
(plain box) : No gravity effect on liquid-vapor behavior and heat transfer

Fig. 6 Expected gravity effects on the interfacial behavior and heat transfer based on the experiments of short microgravity duration [13]



(a) G=150 kg/m^{2}s (b) G=300 kg/m^{2}s

Fig. 7 Simulated gravity effects on thickness of annular liquid film and corresponding heat transfer due to two-phase forced convection [11].

the film flow. These two mechanism supports the experimental result in **Fig. 4**. It is important that there are three mechanism of gravity effect conflicting each other in this regime. The situation is depicted in Mode 3, **Fig. 5** [7]. The gravity effect disappears when mass velocity changes from G=150 kg/m^{2}s to 600 kg/m^{2}s. The observed gravity effect on the heat transfer due to two-phase forced convection is not large at G=150 kg/m^{2}s, however, the effect seemed to be increased at lower mass velocity.

When heat flux is increased to initiate nucleate boiling in the annular liquid film flow, the effect of gravity disappears. The generated bubbles collapses at the surface of liquid film independent of gravity level as shown in Mode 4, **Fig. 5**. The situation is similar to that by the reduction of mass velocity up to G=100 kg/m^{2}s, where nucleate boiling starts again at moderate heat flux by the reduction of mass velocity [12]. The reduction of velocity in the liquid film flow increases the temperature in the vicinity of the heated tube wall which makes the bubbles to grow in the liquid film.

From the results described above, the effect of gravity seems to exist only in the limited range of mass velocity and heat flux. **Figure 6** summarizes the effects of gravity on the two-phase flow behaviors and heat transfer including those expected by the present authors [7]. To confirm the trends of gravity effect observed in the annular flow regime described above, the momentum equations for liquid and vapor flows and the energy equation in the liquid flow were solved by using a simple model. The results are shown in **Fig. 7**, where the enhancement of heat transfer at 2G and the deterioration of heat transfer in μG (0.01 G) are reproduced well. The decrease of gravity effects with the increase of vapor quality or mass velocity are also well reproduced. Increase of vapor quality implies the increase of inertia force like the increase of mass velocity. It is obvious that the existence of gravity effect on the heat transfer should be evaluated in the presence of other forces dominating the phenomena, such as the inertia and the surface tension force as is discussed in detail in the latter section. The thickness of annular liquid film changes

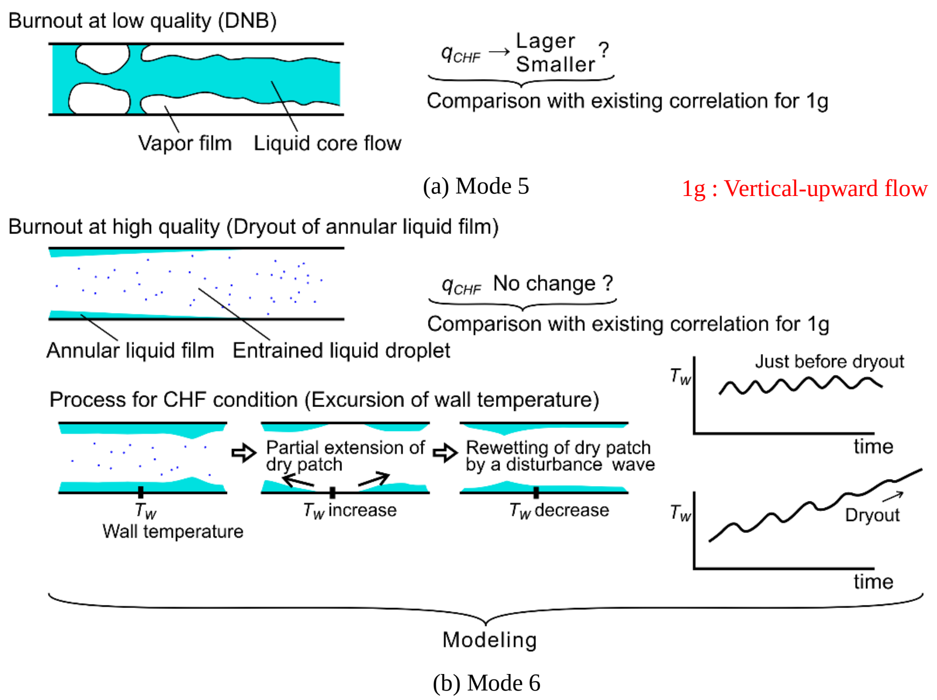


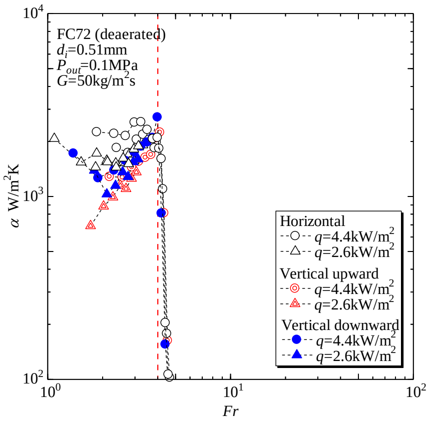
Fig. 8 Gravity effects on critical heat fluxes and their mechanisms for vertical-upward flow [7].

with gravity, where smaller thickness in 2G and larger thickness in μG are confirmed by the simulation. However, not only the film thickness determines the tendency of the heat transfer, but the turbulence plays an important role on it. According to the simulation the turbulence also decreases in μG as was already mentioned. The opposite trends are also reported especially about the gravity effect on the thickness of annular liquid film in the existing experimental results. Because the existing data is quite fragmentary, a series of experiments under various combinations of experimental parameters is needed before we obtain the conclusion.

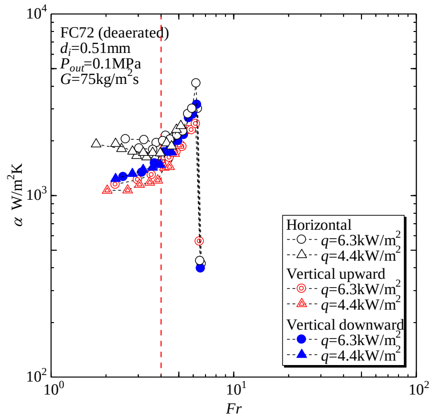
2.3 Gravity effect on CHF conditions

To define the value of CHF is quite difficult in the experiments of short microgravity duration created by the parabolic flight. Then, there is almost no CHF data in flow boiling. No distinct difference of CHF value between μg and 1G was reported [9], where CHF values were tried to be determined by the supply of two different heat fluxes below and above the value of CHF. The resolution of heat flux was quite coarse, resulting in the lack in the accuracy of measured CHF values.

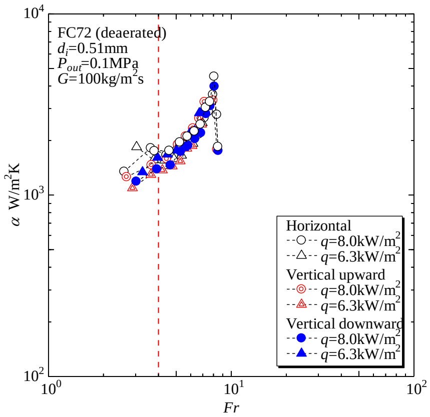
In general, there is two different mechanism of CHF conditions. The one is by the film boiling often referred to as DNB, i.e. departure from nucleate boiling. The mechanism is the transition from the nucleate boiling by the accumulation of vapor on the tube wall which occurs at low vapor quality and high heat flux. Once the film boiling occurs, the surface temperature increases rapidly resulting catastrophic damages for the cooling system. The flow pattern changes from the bubble flow to the inverted annular flow by DNB as shown in Mode 5, **Fig. 8**. The other mechanism is the dryout of annular liquid film encountered at high vapor quality even at low heat flux. The disappearance of annular liquid film does not occurs immediately at the CHF condition but the extension of dry patch and its rewetting are iterated as shown in Mode 6, **Fig. 8**. The dry patch emerges in the interval of consecutive passage of two disturbance waves, and the disturbance wave followed has a role of rewetting it. If the heat flux is slightly lower than CHF, the tube wall with increasing temperature during the period of extending dry patch is cooled down by the quenching of it during the passage of a disturbance wave, resulting in the temperature fluctuation keeping the average temperature almost constant. On the other hand, if the heat flux is larger than CHF, the extension of dry patch is larger and is not quenched enough by the amount of liquid conveyed by the disturbance wave followed. As a consequence, the average value of fluctuated temperature increases gradually. Its rate is accelerated and the range of fluctuation becomes smaller with time by further extension of the dry patches. Gravity effect could exist in the condition of CHF due to DNB, while no gravity effect is expected in CHF due to the dryout of annular liquid film because of the phenomena controlled by the inertia at moderate and high vapor qualities. However, the liquid film thickness might change with gravity and the amount of liquid involved in a disturbance wave is smaller in μg, which implies the dryout could occur at different heat flux or vapor quality in μg. The measurement of exact CHF values and the confirmation of CHF mechanism are expected in a series of ISS experiment.



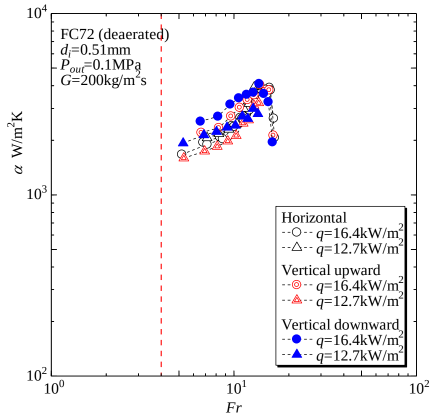
(a) G=50 kg/m^{2}s



(b) G=75 kg/m^{2}s



(c) G=100 kg/m^{2}s



(d) G=200 kg/m^{2}s

Fig. 9 Effects of inertia force on the heat transfer due to flow boiling in a mini-channel of 0.51mm in inner diameter represented by Froude number [14].

2.4 Establishment of dominant force regime map

Effect of gravity is determined in the presence of other forces affecting the phenomena. As was explained in the preceding section, increase of mass velocity and/or vapor quality eliminates the gravity effect. Increase of inertia is realized either by the increase of mass flow rate or velocity. The increase of vapor quality increases the mixture velocity via the decrease of mixture density under the constant mass flow rate. On the other hand, the effect of gravity disappears when the tube diameter is reduced and the surface tension force dominates the phenomena. At least, the body force due to gravity, the inertia and the surface tension should be considered simultaneously when the effect of gravity is discussed. The establishment of the regime map of dominant forces is an important subject because the design of cooling systems becomes more reliable if they are operated under the conditions where gravity effect disappears. The iteration of ground tests will predict the performance similar to that in space. The target of the ISS experiment is to clarify the range of operating parameters where gravity effect on the heat transfer coefficients disappears. The dimensionless groups to correlate the experimental data are Froude, Bond and Weber numbers representing the ratios of the inertia to the body force, the body force to the surface tension and the inertia to the surface tension, respectively.

$$Bo = \frac{(\rho_l - \rho_v) g {d_i}^2}{\sigma} \tag{1}$$

$$We = \frac{\rho_m {u_m}^2 d_i}{\sigma} = \frac{G^2 d_i}{\rho_m \sigma} \tag{2}$$

$$Fr = \sqrt{\frac{We}{Bo}} = \frac{G}{\sqrt{\rho_m(\rho_l - \rho_v) g d_i}} \tag{3}$$

$$\rho_m = \frac{1}{\{x/\rho_v + (1-x)/\rho_l\}} = \frac{G}{u_m} \tag{4}$$

where, ρ_m and u_m means density and velocity of liquid and vapor mixture, respectively.

Before the ISS experiment, the boundaries are examined through the experiments on flow boiling by using thin tubes [14], where their orientation is varied to examine the existence of gravity effect. The first experiment is performed by the use of a tube with a diameter of d_i= 0.51 mm increasing vapor quality under constant mass velocity. Because of large scattering of data inherent in the experiment on flow boiling in thin tubes resulted from the difficulty to evaluate the heat loss, the trend of data is not easy to be interpreted, while the increase of heat transfer

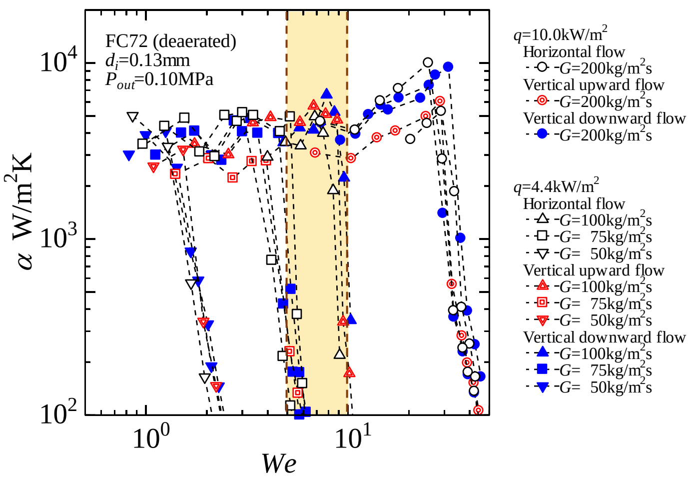


Fig. 10 Effects of inertia force on the heat transfer due to flow boiling in a mini-channel of 0.13mm in inner diameter represented by Weber number [14].

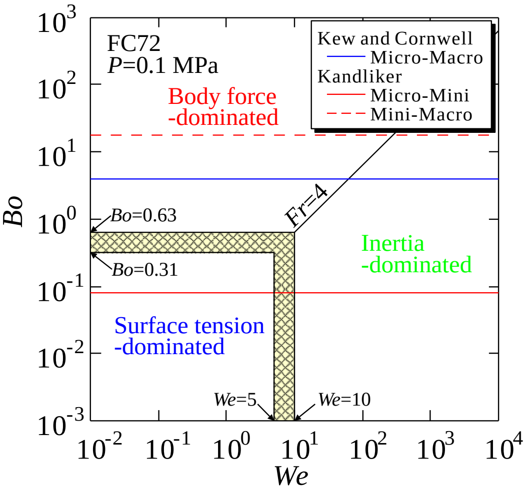


Fig. 11 Boundaries for dominated regimes of body force, inertia, surface tension represented by *Fr*, *We*, *Bo* numbers. [14].

coefficient with increasing vapor quality is clear. With increasing vapor quality, the heat transfer mode is changed from that of the body force dominated to that of the inertia dominated. Independent of mass velocity, the boundary is approximately defined as *Fr*=4 as shown in **Fig. 9**. The value of Bond number can be reduced not only by the reduction of gravity but also the reduction of tube size as is clear from the definition of *Bo* in Eq.(1). To define the boundary between the regime of the surface tension dominated and that of inertia dominated, the heated tube with diameter of 0.13mm is employed. The scattering of data is more pronounced for the smaller tube, but the difference in the trend of heat transfer coefficient against Weber number is recognized at the boundary of *We*=5-10 as shown in **Fig. 10**. The minimum and the maximum boundaries are indicated on the map of dominant force for the heat transfer coefficient in **Fig. 11**, where the boundary between the body force dominated and the surface tension dominated is given by the intersection of other boundaries as *Bo*=0.31-0.63. These boundaries are checked again by the results of ISS experiment where the value of Bond number is decreased by the reduction of gravity level.

2.5 Measurement on flow behaviors

The evaluation of pressure drop especially due to the friction is needed also for the design of cooling system operated under microgravity conditions. As the first step, a flow patter map with the boundaries of flow regimes is to be established. The mechanism of flow pattern transition is also an important subject in the analysis of the results from ISS experiment, where the formulation of boundary is performed with reference to the existing correlations for 1G and μG. In addition to the flow pattern identification, to clarify the difference in the frictional pressure drop between μG and 1G is very important for the design of thermal management systems in space, where the evaluation of void fraction for a vertical upward flow in 1g becomes a key to obtain the reference value. Another important role to clarify the flow behaviors is to utilize them for the analysis of mechanisms for heat transfer characteristics including those of CHF conditions. Especially, the transition of film thickness due to the passage of disturbance wave in the annular flow regime becomes a key to clarify the effect of gravity on the heat transfer due to two-phase forced convection.

3. Outline of ISS experiment

3.1 Requirements for experimental setup

The subjects of ISS experiment from the view point of the measurement are to acquire the data under various combinations of experimental parameters utilizing the long-term duration of microgravity environment, and to obtain the data concerning the flow structures for the clarification of heat transfer mechanisms. For the first objective, the variable parameters as mass velocity, inlet subcooling or vapor quality and heat flux are combined under almost the same pressure condition. Because of the restriction in the length of a heated tube integrated in the experimental setup which has a size to fit the specification of experimental rack, the vapor quality is adjusted in a wide range of heat fluxes by the aid of a preheater. The subcooling or vapor quality at the inlet of the heated test section is adjusted by the preheater located at the upstream. To obtain the CHF data, the toughness of the heated section against the temperature excursion is required. On the other hand, to meet the second subject described in the beginning of the present section, the real-time observation of phenomena during the boiling process is required. To satisfy these conflicting requirements, two test sections of a metal heated tube and a transparent heated tube are

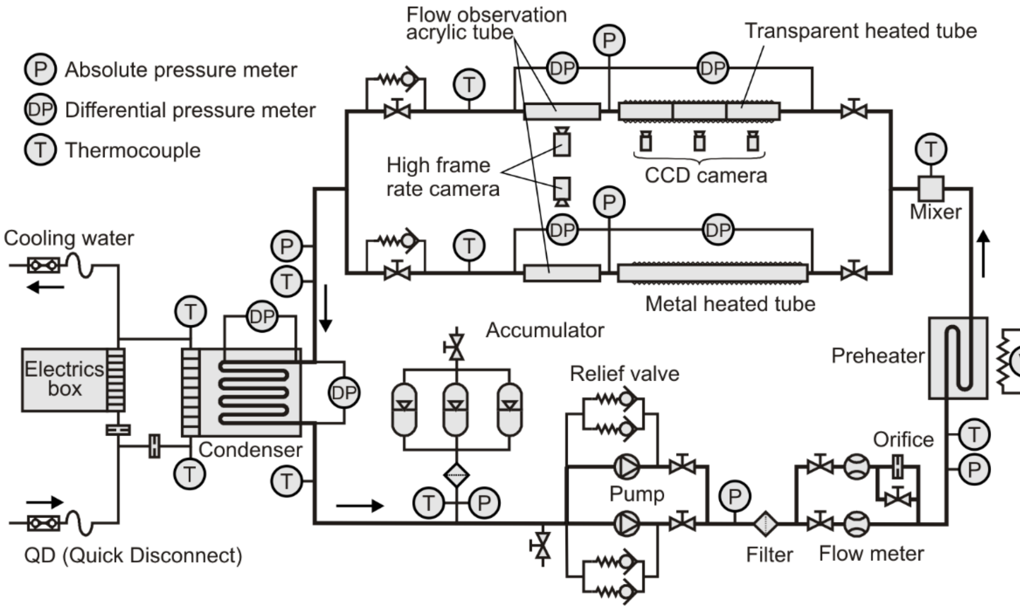


Fig. 12 Outline of test loop for flow boiling onboard ISS with a design reflecting objectives of experiment [18].

connected in parallel with the test loop. In addition to the heated test sections, an unheated section for the observation is connected in the downstream of each heated section to obtain the data for detailed structures of liquid-vapor interfaces and their dynamic behaviors. To acquire the steady-state data, the amount of energy as much as that by power input should be dissipated from the test loop. A cold plate using the circulating water in "KIBO" module is employed contacting the outer surface of the condenser duct.

The test loop for flow boiling requires many components in addition to the tubes and valves and circulating pumps and flow meters. JAXA MSPR (Multi-purpose Small Payload Rack) already transported to "KIBO" has a large work volume for users, i.e. around 900 mmW×700 mmD×600 mmH. However, the entire experimental system including inverters for power supply, data acquisition systems, cameras and data storage, etc. are requested to be prepared by the users. The power supplied to the system is limited to 300 W after the conversion of voltage and current. The limitation of power restricts the range of experimental parameters. However, to identify the boundaries of gravity-dependent and gravity-independent regimes, it is required to realize moderate vapor quality at least for G= 300 kg/m^{2}s under the limitation of power supply. Then, pure n-perfluorohexane is selected as a test liquid because of its small latent heat of vaporization. Furthermore, the bubble size of n-perfluorohexane is quite small compared to water. Then, even the small tube of 4 mm in inner diameter are not regarded as a mini-tube where the liquid and vapor flow behaviors and corresponding heat transfer characteristics are different from those in normal tubes under the pressure near the atmospheric [15, 16].

3.2 Structure of setup and experimental conditions

The test loop has two different heated sections of a metal heated tube and segments of transparent heated tubes connected in series. They are integrated in the test loop in parallel in the downstream of a preheater, and are switched by the manual valve operation by the crews of ISS. The metal heated tube made of copper is employed for the measurement of local heat transfer coefficients along the tube axis and the measurement of CHF values. To avoid the high temperature on the outer surface of electric sheath heaters, a copper tube is employed for the reasons of protection of heaters from the damage and of the safety during the space experiment. The heated length of the metal tube is 368 mm. On the other hand, the transparent heated tube makes possible the observation of liquid-vapor interfacial behaviors and acquisition of heat transfer data simultaneously. On the inner wall of a Pyrex glass tube with I.D. 4 mm/O.D. 6 mm, a thin gold film of 0.01 μm-order thickness is coated uniformly. The tube is heated by the supply of DC current directly through the gold film, while the film operates as a resistance thermometer to evaluate the average inner wall temperature across the heated length. [17]. The heated section is divided into three segments of the transparent tubes with lengths of 50 mm, 50 mm and 7mm. The short segment connected at the downstream is used to clarify the temperature oscillation just before CHF conditions as mentioned in the preceding section. Although the heat transfer coefficients due to nucleate boiling are not the same between the metal heated tube and the transparent heated tube, the discussion on the gravity effect is possible with reference to the terrestrial data obtained from the tubes with the same specification.

An unheated test section is connected at the downstream of each heated section for the observation of interfacial behaviors and for the measurement of pressure drop, void fraction, and annular liquid film thickness including the motion of disturbance waves. The knowledge is reflected to the analysis of heat transfer mechanisms corresponding to the heat transfer data obtained at the upstream. High-speed video is introduced to the unheated sections. The outline of the test loop is shown in **Fig. 12** [18].

To evaluate the gravity effect, the reference experiments are performed on the ground for a vertical-upward flow. The vertical flow makes the easier comparison both of interfacial behaviors and heat transfer characteristics between different gravity levels. The vertical flow realizes nearly axisymmetric liquid-vapor behaviors independent of gravity and almost uniform heat transfer along the circumferential direction of the tube wall. In the case of the horizontal flow, the drastic change in the distribution of the continuous phase makes the interpretation of gravity effects more difficult. **Table 1** shows the outline of experimental conditions.

Table 1 Experimental conditions in ISS.

Power supply to heaters	300 W
Test fluid	n-perfluorohexane
Inner diameter of heated sections	d_i = 4 mm
Heated length	l = 50 mm×2+7 mm×1 for transparent heated tube l = 368 mm for metal heated tube
Mass velocity	G = 30–400 kg/m^{2}s
Liquid subcooling at inlet of heated test section	ΔT_{sub} = 0–30 K
Vapor quality at outlet of heated test section	x = 0–1
Heat flux	$q < 1\times10^6$ W/m^2

4. Conclusions

The experiment on the fundamental scientific research on flow boiling has not yet been conducted onboard space shuttle or international space station in despite of a long history of space utilization researches. The experiment described here attracts much attention of investigators in the world working in the same discipline. The experimental data obtained after the successful operation of the experimental setup is to be analysed by the international team of nine organizations in Europe, Russia, China and US in addition to six organizations in Japan.

In this paper, the outline of flow boiling experiment was described concentrating on the subjects of the experiments and their objectives.

1) Boiling and two-phase flow system is useful and also unavoidable for the thermal management systems in future, where both of the amount of thermal energy dissipated from the space platforms and the heat flux density form the electric equipment and semiconductor chips are increased.
2) The knowledge derived from the experimental data and the observations of interfacial phenomena is applied not only to the design of high-performance space thermal management systems but also the cooling systems on the ground accompanied by the variation of acceleration, e.g. inverter cooling systems for automobiles and two-phase flow systems where the downward flow cannot be avoided.
3) The establishment of dominant force map is one of the important objectives because it clarifies the gravity-dominated regime in the presence of the inertia and the surface tension force. The design of space two-phase systems operating free of gravity effect has more reliability because the operation in space is similar to that by the grand tests. In the preliminary research, the location of the boundaries for the dominating regimes represented by dimensionless groups were tentatively decided by the data from the flow boiling experiments using mini-tubes.
4) The setup designed for ISS experiments has three test sections; i) a metal heated tube for the acquisition of heat transfer data due to flow boiling along the tube axis and the data for critical heat flux conditions, ii) a transparent heated tube for the acquisition of heat transfer data and for the simultaneous observation of liquid-vapor behaviors, iii) unheated test sections located at the downstream of the heated test sections for the detailed observation and the measurement of liquid-vapor interfacial behaviors and for the acquisition of data for the elementary processes to be used in the analyses of heat transfer mechanisms.

The experiments onboard ISS is scheduled in Japanese fiscal year of 2016.

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